10/579692

IAP20 Rec'd PCT/PTO 16 MAY 2006

AMPLIFIER PROVIDED WITH A REGULATION SYSTEM CONTROLLED BY THE OUTPUT STAGE

[0001] The invention relates to an amplifier with output-stage-controlled regulation and to a method for output-stage-controlled regulation of an amplifier.

[0002] Often, electrical amplifiers have a two-stage construction. In a first stage, an intermediate circuit generator or a power supply unit generates a supply voltage of medium height or precision. The supply voltage supplies an output stage, which has the task of generating an output signal with the desired properties. Depending on requirements, the output signal may have a voltage that is transformed upward compared to the supply voltage and depending on the application may have predeterminable constant or time-dependent signal courses. For use as a gradient amplifier for gradient coils in magnetic resonance systems, especially fast-time dependent output signal courses that must be adhered to precisely must be assured. The electronics of the output stage can be adapted such that when supplied with the requisite supply voltage, an output signal with the desired properties can be generated, given the most efficient possible construction.

[0003] The precision with which the desired parameter values of the output signal, such as current or voltage, can be adhered to depends, among other factors, on fluctuations in the supply voltage. Under some circumstances, fluctuations in the supply voltage can be partly compensated for by means of the circuitry of the output stage. However, complete compensation is not always possible, and hence not all the requirements made of the output signal can readily be met.

[0004] With a view to the quality of the output signal, a stabilized power supply unit is therefore employed as a rule. In addition, the desired parameter of the output signal can be regulated, and the regulator for instance regulates switching times of switch elements of the output stage. Such regulation can be adapted optimally to the desired mode of operation of the output stage, so as to minimize the effects of a fluctuating supply voltage. Nevertheless, at critical operating points, for instance when the time-dependent courses of the output

signal are changing rapidly, it must be observed that an influence of the power supply signal is preserved. Depending on the demands made of the output signal, additional compensation for supply fluctuations can therefore be desirable.

[0005] The object of the invention is, for a two-stage amplifier, to create an additional possibility of compensating for fluctuations in a parameter of the energy supply.

[0006] The invention attains this object with an amplifier having the characteristics of independent claim 1 and by means of a method having the characteristics of independent claim 10.

[0007] A fundamental concept of the invention is to disclose an amplifier having an output stage which can be supplied by an electrical energy source, the output stage is connected on the input side to a control device, by whose control signal an output signal, dependent on a parameter value of the energy source, of the output stage is controllable. An output stage may also comprise a plurality of series-connected individual output stages, which are supplied from potential- free energy sources. For additional compensation for fluctuations in the energy source, a compensation device is provided, which is connected to the energy source and to the control device, and by which the control signal is variable as a function of the value of the parameter.

[0008] The advantage of this construction is that fluctuations in the energy source need not first be detected in the output signal of the output stage in order to be capable then of being compensated. Instead, they are already detected as they occur and before an output signal is generated. Their influence on the function of the output stage is already taken into account in the control signal for the output stage, and therefore compensated for in advance, or in other words proactively. Therefore particularly fluctuations at critical operating points, for instance when rapid changes in the output signal are occurring, which are often connected to an overswing because of the mode of operation of the control of output stage, are suppressed, without additional sources of error, such as the aforementioned overswing being capable of affecting the compensation. Thus the compensation is

effected in a way that is directly dependent on the signal to be compensated for and independently of other, unwanted influencing variables.

[0009] In a further feature of the invention, a regulation system is provided which is connected on the input side to the output stage and on the output side to the control device, and by whose regulator signal the control signal can be regulated as a function of the output signal of the output stage. The regulation system is connected to the compensation device, and by means of the compensation device, the regulator signal is variable as a function of the value of the parameter of the energy source.

[0010] As a result, the advantage is obtained that the output signal of the output stage can initially be regulated as stably as possible by the regulation system, and that the compensation device accomplishes an additional stabilization. Combining the two devices brings about especially reliable stabilization of the output signal. In a further advantageous feature of the invention, the compensation device is embodied such that it can generate a compensation signal that is dependent on the parameter and on a nominal or maximal value of the parameter. As a result, an operating range for the compensation signal is predetermined that stands in relation to the desired signal of the energy source and therefore maintains an operating range adapted to it. As a result, for different nominal or maximal values of the energy source, an overswing from an excessively great variation in the compensation signal can be avoided.

[0011] A further fundamental concept of the invention comprises a method for controlling an amplifier having an output stage which is supplied by an electrical energy source, including the following steps:

[0012] ascertaining a parameter value of the energy source,

[0013] generating a compensation signal as a function of the parameter value,

[0014] generating a control signal as a function of the compensation signal,

by means of the output stage, generating an output signal as a function of the control signal.

[0015] This has the advantage that

[0016] Ffluctuations in the energy source can be directly detected and used for compensation. As a result, other, indirect influencing variables, which may be due to the control or mode of operation of the output stage, for instance, are not taken into account and cannot; as sources of error, have may not have an effect on the compensation and the .compensation that of the output stage is directly dependent on the energy source brings about a stabilization of the output signals of the output stage.

[0017] In an advantageous feature of the method, the following further steps are included:

[0018] ascertaining a parameter value of the output signal,

[0019] generating a regulator signal as a function of the parameter value of the output signal,

[0020] generating the control signal as an additional function of the regulator signal.

[0021] The combination of the method steps for direct compensation of fluctuations in the energy source and for regulating the output signal of the output stage brings about an additional, as it were double, stabilization of the output signal.

[0022] The amplifier and the method, as a function of a supply voltage, can generate an output voltage which is stabilized by the compensation device. The regulation system can also regulate the output voltage on the basis of the current induced in a coil by the output stage.

[0023] The proposed voltage-dependent, current-regulated amplification can be employed especially advantageously as a gradient amplifier for a gradient coil in a magnetic resonance system, where a coil current changes or in other words gradients that must be adhered precisely must be generated in rapid chronological succession in order to generate rapidly changing magnetic gradient fields.

[0024] Further advantageous features of the invention are the subject of the dependent claims and will become apparent from the description.

Exemplary embodiments of the invention are described in further detail below in conjunction with drawings. Shown areFig. 1, a regulated two-stage amplifier with a compensation device;

Fig. 2, a regulated two-stage amplifier with a compensation device and a regulator signal amplification device;

[0025] Fig. 3, the course of the control signal of the output stage as a function of the regulator signal;

[0026] Fig. 4, the course of the output signal of the output stage as a function of the control signal;

Fig. 5, the schematic construction of a PI regulator with D control and controllable regulation parameters;

Fig. 6, the digital construction of a D regulating element; and

Fig. 7, the digital construction of an I regulating element.

[0027] Fig. 1 schematically shows a regulated two-stage amplifier 25 with a compensation device 9. The amplifier 25 has an electrical energy supply E0, which supplies an output stage 6. The output stage 6 generates an output signal Uout, which is used to drive a load 8, shown here as a coil.

[0028] A parameter value of the output signal Uout is ascertained by a measuring device 7 and is delivered to a regulation system 1 via an actual value line 3, additionally followed in the drawing by the letter A for "actual". As a further signal input, the regulation system 1 has a nominal value line 2, which is additionally followed in the drawing by the letter N for "nominal". The regulator signal RS is delivered to the control device 4 via a regulator output line 5, and the control device is connected to the output stage 6 via four signal lines (or correspondingly more in the event of a series circuit of more output stages) for the control signals MS1 through MS4.

[0029] The output stage 6 has a circuit arrangement with a smoothing capacitor, not identified by reference numeral, and four switches S1 through S4 and free-wheel diodes, not identified by reference numeral, connected parallel to

them. The switches S1 through S4 are triggered by the control signals MS1 through MS4. As a result, output voltages of the output stage can be generated whose value, averaged over one switching period, can be between the positive supply voltage +U0 and the negative supply voltage -U0.

[0030] The supply voltage U0 is made available by the energy supply E0 and is therefore subject to fluctuations in the energy supply. As a consequence, the output signal Uout of the output stage 6 is also subject to these fluctuations.

[0031] To compensate for these fluctuations, a compensation device 9 is provided. As its output signal, the compensation device 9 generates a compensation factor k, or its reciprocal value 1/k. The compensation factor k depends, in a manner to be described in further detail hereinafter, on a parameter value of the energy supply E0. It is delivered to the regulation system 1 or the control device 4 via the compensator output lines 11 or 13, or the reciprocal value 1/k is delivered to the control device 4 via the compensator output line 14. The compensator output lines 11, 13, 14 are redundant in the sense that all that is needed for compensation by the compensation device 9 is one of the three compensator output lines 11, 13, 14. In this sense, they can be understood as alternatives to one another.

[0032] The amplifier 25 shown may, for instance as a function of a supply voltage U0, generate an output voltage Uout, which is stabilized by the compensation device 9. In that case, the compensation device 9, as a parameter of the energy supply E0, ascertains the voltage thereof, that is, the supply voltage U0. By measuring the output stage supply voltage U0, the voltage incursions of the output stage, which occur from a change in the load on the output stage, are jointly compensated for as well. Moreover, the measuring device 7 can be a current measuring device, which measures the current induced in the coil 8 by the output voltage Uout of the output stage 6. This kind of voltage-dependent, current-regulated amplifier 25 may be used for instance as a gradient amplifier in a magnetic resonance system, where in rapid chronological succession changes in the coil current, or in other words gradients, must be generated in order to generate rapidly changing magnetic gradient fields.

[0033] In Fig. 2, an amplifier 26 is shown, with a compensation device 9 that is modified compared to Fig. 1 described above. The output stage 6 with the regulation system 1 and the control device 4 correspond to the descriptions above and are identified by the same reference numerals. The compensation device 9 likewise, as described above, generates a compensation factor k as a function of a parameter value of the energy supply E0. The compensation factor k is delivered to a regulator signal amplification device 10 via the compensator output line 12. The regulator signal amplification device 10 is connected on the input side to the regulator output line 5, and it amplifies the regulator signal RS as a function of the compensation factor K. In this way, the compensation device 9 acts on the controller of the output stage 6.

[0034] In Fig. 3, the course of the control signals MS1 and MS4 is shown as a function of the regulator signal RS. The regulator signal RS is capable of assuming values within an arbitrarily defined signal range from -RS0 to +RS0. The control device 4 may be an analog or digital modulator, which via the signals MS1 through MS4 triggers the switches S1 through S4 of the output stage 6, for instance in such a way that the switches S1 and S4 are opened or closed simultaneously, as are the switches S2 and S3.

[0035] In an analog modulator, the regulator signal RS is typically a voltage, which is compared in the modulator with a triangular voltage as a comparison variable. If RS is greater than the instantaneous value of the triangular voltage, then the signals MS1 and MS4, for instance, can be set for closing the switches S1 and S4. Conversely, if RS is less than the instantaneous value of the triangular voltage, then MS2 and MS3 can instead be set, so that the switches S2 and S3 are instead closed. In a digital modulator, the comparison variable may be a counter state. If the regulator signal RS, present in the form of a number, is greater than the counter state, then once again MS1 and MS4 can for instance be set, while conversely if RS is less than the counter state, then MS2 and MS3 can be set instead.

[0036] If the switches S1 and S4 are closed and S2 and S3 are open, then the resultant output voltage Uout is the voltage +U0; conversely, if S2 and S3 are

closed and S1 and S4 are open, then the resultant output voltage Uout is the voltage - U0. If the switches are opened and closed in alternation after the modulation mode, the result, as an average value of the output voltage Uout, is a voltage which is between +U0 and -U0 and which depends on the switching times of the switches S1 through S4.

[0037] The course shown for the regulator signal RS can accordingly mean for instance that at -RS0, the signals MS1 and MS4 are not set, and the signals MS2 and MS3 are not set. By way of a linearly rising course with the regulator signal RS, the signals MS1 and MS4 as well as MS2 and MS3 are set and opened in alternation with modified switching times, while at a regulator signal of 0, the switching times for S1 and S4, on the one hand, and S2 and S3, on the other, are of equal length, until then, at a regulator signal of +RS0, now only the signals MS1 and MS1 are set, while MS2 and MS3 are not set.

[0038] In Fig. 4, the output signal of the output stage Uout is plotted over the control signals MS1 through MS4. Based on the output signal -U0 with the signal for MS1 and MS4 not set (in return, MS2, MS3 are set at 100%), the output signal rises up to a value of zero, when the switching times for MS1 and MS4 on the one hand and MS2 and MS3 on the other are of equal length. If the switching times shift further, such that only MS1 and MS4 are set, then the output signal rises further linearly, until the maximum value of +U0 for the output signal of the output stage Uout is reached.

[0039] Together with the above description of the drawings, for the range of the regulator signal RS of from -RS0 to +RS0, a regulating range for the output signal Uout of from - U0 to +U0 thus results.

[0040] For the relationship among the control signals MS1 through MS4 and the regulator signal RS, the following equation applies:

$$MS2,3 = 100\% - MS1,4;$$

in this illustration, the control signals MS1 through MS4 are understood as a percentage of the time during which the respective control signal is set. In other

words, at the value of 100%, for instance, MS1 and MS4 are constantly set, while at the value of 75%, for instance, they are set 75% of the time. If the regulator signal RS is added, then for the relationship between the control signals MS1,4 and the regulator signal RS, the following equation applies:

$$MS1{,}4 = 50\% + RS * 50\% / RS0.$$

For the relationship between the control signals MS1,4 and the output signal of the output stage Uout, the following equation applies:

$$Uout = (U0 / 50\%) * MS1{,}2 - U0.$$

The amplification of the output stage 6 is obtained by inserting the above relationship for MS1,4 into the preceding relationship for Uout:

$$Uout = (U0 / 50\%) * (50\% + RS * 50\% / RS0) - U0,$$

and from the above, by conversion:

$$Uout = U0 * RS / RS0.$$

As a result, for the amplification V of the chain comprising the control device 4 and the output stage 6, the following equation is obtained:

$$V = U0 / RS = Uout / RS0.$$

[0041] The output signal Uout of the output stage 6 is thus linearly dependent on the regulator signal RS. However, there is also a dependency on the supply voltage U0. In the event of a supply voltage U0 that is not stabilized or is only insufficiently stabilized, for instance if fluctuations occur in the mains voltage or in the event of a rapidly varying load, an influence on the regulation properties becomes apparent. Since as a rule the goal of a modulation method is to achieve a linear relationship between the output signal of an output stage and its regulator signal, these concepts logically also apply to other modulation methods not described in detail.

[0042] From the preceding equation, it can be seen that compensation for fluctuations in the supply voltage U0 is possible by means of a compensation factor K, for which the following applies:

$$k = UN / U0,$$

UN represents a nominal or typical supply voltage, for instance the maximum supply voltage. For compensation, either the regulator signal RS is multiplied by the compensation factor k, or the range of the regulator signal is increased by factor 1/k, so that the range limits are at RS0 * 1/k.

[0043] From the above-described Figs. 1 and 2, it can be seen that the compensation factor k, or its reciprocal 1/k, is delivered to either the regulation system 1, the control device 4, or the regulator signal amplification device 10.

[0044] In Fig. 5, as an example of a regulator included in Fig. 1, a PID controller with D control and adjustable controller parameters is shown. The nominal value N is delivered to a branch that has the D element 16, and the amplification of the D element 16 is adjustable by means of the D-signal amplifier 17. The D-signal amplifier 17, as its input signal, receives the compensation factor k, or a value proportional to it, via the compensator output line 11. The amplified output signal of the D element 16, DS, is delivered to an adder.

[0045] The nominal value N is also delivered to a delay element DEL (delay), and from there it is delivered to a differentiator (DIFF). The differentiator DIFF furthermore receives the actual value A as its input signal and forms the control difference between the nominal value N and the actual value A. The control difference is delivered both to the adjustable P element 18 and to the I element 19 and from there to the I-signal amplifier 20. The adjustment of the P element 18 and of the I-signal amplifier 20 is also effected by the compensator output line 11, by way of which the compensation factor k or a value proportional to it is delivered. The P- signal PS and the I-signal IS, like the D-signal DS, are delivered to the adder SUM, which from them forms the regulator signal RS. The described

digital and adjustable PID controller 15 may be used as a regulation system in the above-described amplifier of Fig. 1 or Fig. 2.

[0046] The amplifiers 17, 18 and 20 required anyway for adjusting the control parameters "P", "I" and "D" can be used here for adjusting the compensation factor as well, making one additional amplifier device 10 is advantageously unnecessary.

[0047] In Fig. 6, a simple digital construction for the D element 16 is shown. The nominal value N is delivered to an n-bit-wide memory, a D flip-flop DFlip, and to an m-wide subtractor SUB. Preferably, let m = n + 1. DFlip is clocked here by the clock signal CLK, and the clock rate can be lowered by the signal CLK-enable, for instance if CLK is supposed to be a high-speed system clock signal.

[0048] The rise response of the described digital D element, on the condition that m = n + 1, would be shown in table form as follows, for example:

Takt	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
N	0	0	2	4	6	8	8	8	8	8	6	4	2	0	0	0
Q		0	0	2	4	6	8	8	8	8	8	6	4	2	0	0
Out		0	2	2	2	2	0	0	0	0	-2	-2	-2	-2	0	0

[0049] In Fig. 7, a digital design of the I element 19 is shown. The input signal IN, which in a PID controller is the control difference signal, is delivered to an adder ADD. The output signal of ADD is delivered to a D flip-flop DFlip, which is clocked by a clock signal CLK and can be lowered in its clock rate by the signal CLK-enable. The output signal Q of DFlip is delivered to a further input of ADD. Thus the output signal of the adder ADD is at the same time the input signal of the amplifier 20. Alternatively, as the output, the output Q of DFlip can be used, which in comparison to the output of ADD appears later by one clock signal. The jump response of the I element described can for instance have the following appearance, assuming as a starting condition Q = 0:

Takt	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
N	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Q	0	0	0	0	1	2	3	4	5	6	7	8	9	10	11	12
Out	0	0	0	1	2	3	4	5	6	7	8	9	10	11	12	13

[0050] An analog integrator, at a time constant corresponding to a clock signal length and an input voltage that in the above-indicated time pattern varies from zero to 1V, at a starting condition of 0V, likewise would have an output voltage which varies with 1V per clock signal length, as in the above-indicated time pattern. As can be seen from these two examples, both analog and correspondingly constructed digital regulator circuits are fundamentally equivalent in their functional principle and in their regularities.

[0051] If the compensation is to be done by the compensation factor k or its reciprocal in the control device 4, then with a digital control device, which has one or more analog-to- digital converters for converting an analog regulator signal RS, the multiplication of the regulator signal RS by the compensation factor k is done in the analog-to-digital conversion in that an external reference input of one of the analog-to-digital converters is used for the standard of the conversion in accordance with 1/k. For a fully digital control device 4, the digital regulator signal RS can be multiplied by the compensation factor k. In an analog control device 4, a favorable circuit variant can result by multiplying the comparison variable (triangular voltage) by the reciprocal of the compensation factor, that is, 1/k. The compensator output line 14 described in conjunction with Fig. 1 is used.

[0052] For the compensation factor k, in view of practical application of the amplifier, limit values can be specified. For instance, if the supply voltage U_0 is tending toward zero, then the compensation factor k would tend toward infinity. Useful operation of the amplifier, however, is not possible at extremely low supply voltages U_0. A practical design could therefore be limited to supply voltages U_0 that at maximum are approximately 30% below the rated value of the supply voltage U_0 or approximately 40% above the maximum value of the supply oltage.

For supply voltages U_0 outside these limit values, the compensation factor k could then be kept constant.

[0053] In the description of the relationship between the output voltage of the output stage and the regulator signal, a linear relationship has been assumed in idealized form. Even if this ideal relationship does not in fact exist, for instance because of safety margins in the triggering of the output stage switches to avoid short-circuit triggering, the restriction to a useful operating range means that adequate precision of the compensation can still be achieved. If not, then the nonlinearities can be taken into account in ascertaining k.